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CALORIMETRIC DETERMINATION OF RELATIVE GAMMA HEATING IN MATERIALS OF VARIOUS THICKNESSES AND ATOMIC NUMBERS

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16. Abstract

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SUMMARY

A calorimeter was constructed to determine the relative amount of gamma heating in different materials as a function of thickness and atomic number. The experiment was performed in the NASA Plum Brook Mockup Reactor, which has a typical light water test reactor gamma source spectrum. Carbon, aluminum, zirconium, tin, and lead specimens in slab geometry were irradiated. The results showed no significant difference in the gamma heating in carbon and aluminum, but the heating in the other materials was greater than that in carbon and aluminum. The smaller thicknesses had the greater heating. The results are believed to be applicable to nuclear reactor experiment designs and to other reactor problems as well.

The calorimeter was also used to determine the gamma heating effect in an irradiation experiment mockup having cylindrical geometry. The result showed good agreement with an expected value calculated from the slab geometry data.

INTRODUCTION

Knowledge of gamma heat generation is important in many nuclear reactor experiments. The gamma heating, in contributing to the heat transfer rates in experiments, may affect the response of instrumentation or the temperatures of irradiation specimens. Means of measuring gamma dose rates with light-element dosimeters are available and convenient to use (ref. 1). However, recent publications (refs. 2 and 3) have indicated that in the same gamma field substantially greater gamma heating, in watts per gram of material, may exist in elements of greater atomic numbers and that there is an effect of thickness. The purpose of this work was to experimentally determine these effects in materials of different atomic numbers and thicknesses in a typical light water test reactor gamma source spectrum.

EXPERIMENTAL EQUIPMENT

A calorimeter was made to accomplish the task. The calorimeter (fig. 1) consisted of a cylindrical aluminum chamber with a thin steel tube enclosed and fastened to one end of the chamber. The specimen being irradiated was fastened to the steel tube, and the temperature difference over the length of the tube was measured by copper-constantan thermocouples. The dimensions were chosen to allow operation in a low power reactor test facility where gamma fields were on the order of 0.02 watt per gram.

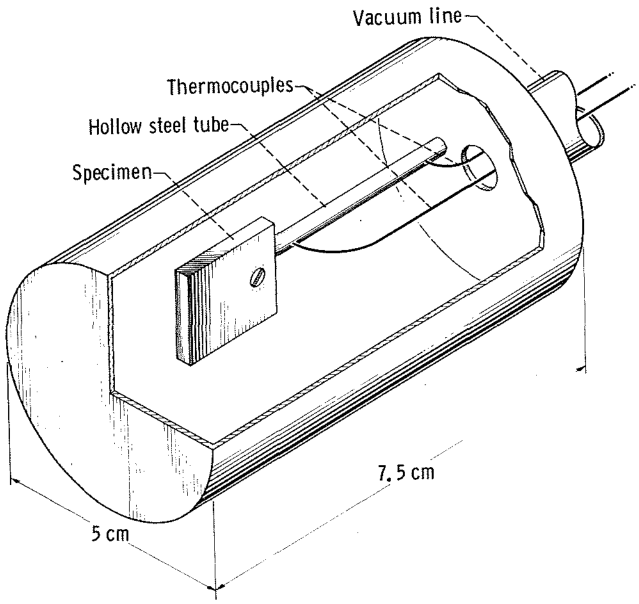

Figure 1. - Calorimeter assembly.

Temperature differences were kept below 20 K to minimize thermal radiation and conduction heat losses. Aluminized Mylar tape was used on all surfaces, and layers of aluminum foil were used for thermal radiation baffles. A vacuum was maintained in the chamber during irradiation using a continuously operating vacuum pump.[1]

The specimens were 1 by 3/4 inch (2.54 by 1.905 cm) platelets, varying only in thickness. Carbon, aluminum, zirconium, tin, and lead were chosen for specimen materials because of their small thermal neutron cross sections and because they span the periodic chart of atomic numbers. (Elements with large thermal neutron cross

[1]The vacuum pump had a capacity of 25 liters/min at 1 atm inlet pressure, with an ultimate vacuum of 10^{-1} torr.

sections would have experienced considerable heating due to (n, γ) reactions, thus confounding the effects of atomic number and thermal neutron cross section.) One hollow aluminum specimen was tested. It had the same outside dimensions as a solid 1/2 inch (1.27 cm) aluminum specimen.

All the irradiations were done in the LA-5 test position of the NASA Plum Brook Mockup Reactor (MUR) at reactor powers of between 10 and 50 kilowatts. Figure 2 shows the placement and orientation of the calorimeter in the reactor.

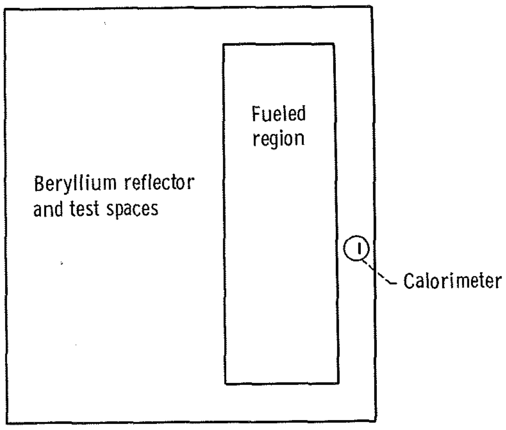

Figure 2. - Plan view of MUR showing location and orientation of calorimeter and specimen.

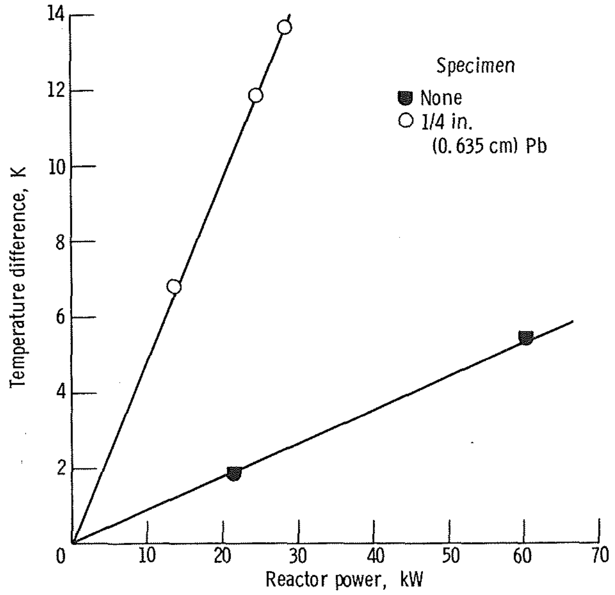

Figure 3. - Response as function of MUR power level.

EXPERIMENTAL DATA

Figure 3 shows some data which indicate the linearity of response of the calorimeter.

Table I summarizes all the data in the order in which they were taken. It shows the actual recorded values as well as the results of two arithmetic operations on the values. The first operation was normalization of all data to 1 kilowatt reactor power. The other operation was a correction for operating time. This was necessary because the reactor fission products did not reach equilibrium during the runs - the gamma heating continues to increase even after several hours of MUR operation. In the MUR the irradiations were terminated when it appeared that thermal equilibrium had been reached.

TABLE I. - SUMMARY OF EXPERIMENT DATA

Run	Specimen material	Nominal thickness		Mass, g	Area, cm^2	ΔT, K (a)	Irradiation time, min	Power, kW	$\Delta T/P$, K/kW (b)
		in.	cm						
1	None	----	-----	0	0	1.67	34	21.7	0.087
2	Sn	1/8	0.316	9.913	12.6	4.73	62	22.2	.226
3	Pb	1/4	.635	34.270	15.8	6.57	75	13.5	.504
4	Pb	1/4	.635	34.270	15.8	11.13	58	24.6	.484
5	Sn	1/4	.635	20.599	15.0	6.91	90	23.9	.296
6	Zr	1/8	.316	9.987	13.0	4.47	46	23.4	.209
7	C	1/2	1.27	11.823	23.5	5.36	78	40.5	.137
8	Al	1/8	.316	4.356	12.7	4.08	65	42.4	.102
9	Al	1/2	1.27	17.015	21.2	7.87	93	44.4	.181
10	Pb	1/8	.316	17.036	12.8	5.92	83	15.3	.398
11	Pb	1/16	.158	9.264	11.9	7.08	120	21.1	.336
12	Al	1/4	.635	8.423	15.8	4.93	82	35.8	.142
13	Zr	1/4	.635	20.222	16.0	10.49	78	36.1	.301
14	Pb	1/32	.08	4.061	10.9	7.88	45	40.0	.217
15	None	----	-----	0	0	5.24	72	60.5	.091
16	Hollow Al	----	-----	3.016	21.9	4.18	85	56.3	.076
17	C	1	2.54	23.053	36.9	6.50	94	37.5	.173
18	Zr	1/16	.158	5.197	11.6	5.56	58	36.8	.161
19	Sn	1/16	.158	5.460	11.4	6.36	57	36.2	.188
20	Al	1/8	.316	4.356	12.7	3.38	68	36.2	.098
21	Zr	1/4	.635	20.222	16.0	9.79	64	35.2	.293
22	Pb	1/4	.635	34.270	15.8	7.64	59	13.9	.586
23	Pb	1/16	.158	9.264	11.9	7.09	60	25.2	.299
24	Pb	1/4	.635	34.270	15.8	12.87	62	28.5	.479

[a]Raw data temperature differences.

[b]ΔT normalized to 120 min of operation.

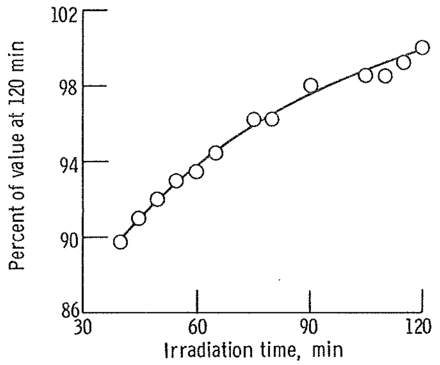

Figure 4. - Response as function of irradiation time. Run 11.

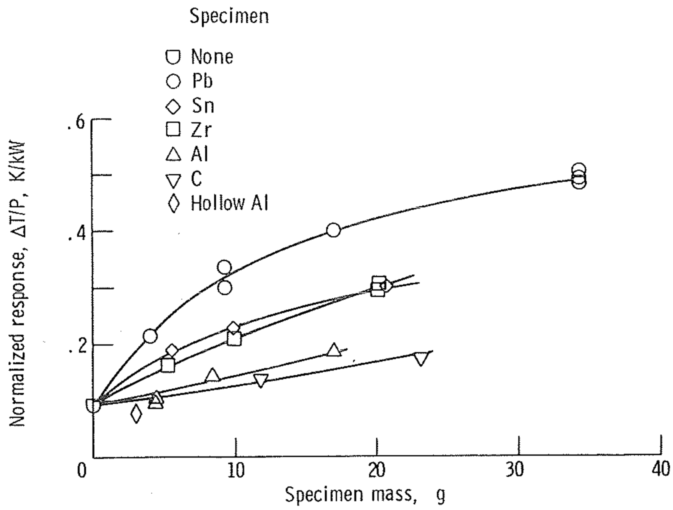

Figure 5. - Normalized response as function of specimen mass.

All data values were corrected to the longest run time of 2 hours using the data from run 11 (fig. 4).

The results of these operations are shown in the last column in table I.

No corrections were made for the effects of thermal neutron flux. It is estimated that thermal neutrons cause approximately 10 percent of the heating in aluminum in this test position in the MUR. The percentage should be smaller for the other materials because the ratio of macroscopic absorption cross section to density is smaller for those materials than for aluminum.

Figure 5 shows the normalized test values plotted against mass of the specimens. The relatively greater response of the heavy-element specimens is evident. The hollow aluminum specimen reduced the response below that with no specimen, indicating there must have been some heat transfer from the surface of the specimen. This was treated as a small negative effect of surface area.

It was assumed that all the data fit the equation

$$\frac{\Delta T}{P} = RK_1M + K_2 - K_3A \tag{1}$$

where

ΔT measured temperature difference over length of steel tube, K

P MUR power, kW

$\Delta T/P$ total response, K/kW

R ratio of heating in a specimen to heating in an aluminum specimen of the same mass

K_1	response factor for aluminum specimen mass, K/(g)(kW)
M	mass of specimen, g
K_2	response with no specimen, K/kW
K_3	response factor for specimen surface area, $K/(cm^2)(kW)$
A	surface area of specimen, cm^2

It was assumed that the response factors aluminum and carbon were not functions of thickness. The coefficients K_1, K_2, and K_3 were determined from the aluminum data, for which R = 1 by definition. K_1 was determined by comparing runs 9 and 16; K_2 was the average response of runs 1 and 15; and K_3 was determined by comparing runs 1 and 15 with 16.

The values of R for all the runs were then calculated using equation (1) rearranged as

$$R = \frac{\frac{\Delta T}{P} - K_2 + K_3 A}{K_1 M} \tag{2}$$

where

$$K_1 = 0.00743\ K/(g)(kW)$$

$$K_2 = 0.0890\ K/kW$$

$$K_3 = 0.00167\ K/(cm^2)(kW)$$

The resulting values of R are shown in figure 6. The reader will note that mass rather than thickness of the specimen was chosen for the abscissa; but since the specimens all have the same area facing the core, that is, vary only in thickness, the abscissa is proportional to density times thickness. Thus the abscissa is proportional to thickness for a given material; the thicknesses tested are shown in table I.

In figure 6 the variation of R is over a maximum range of thicknesses from 1/32 to 1 inch (0.08 to 2.54 cm). For some of the materials the range is only 1/16 to 1/4 inch (0.158 to 0.635 cm). Smaller thicknesses are of interest but are believed to be below the range of accurate measurement with this device. For larger thicknesses it can be expected that each curve eventually intersects the line R = 1.

Figure 6 shows that the heating in aluminum is about 10 percent greater than in carbon; but since about 10 percent of the heating in aluminum is due to thermal neutrons,

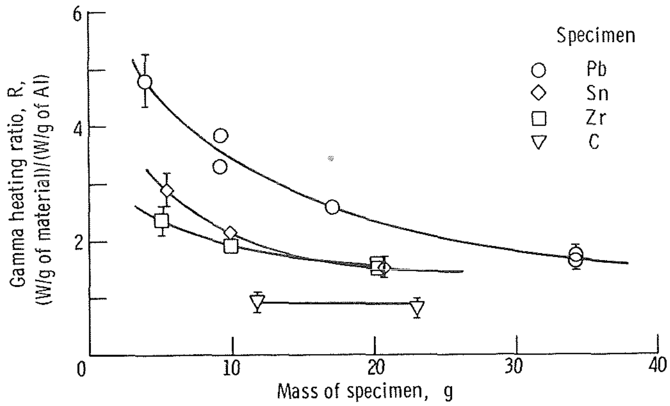

Figure 6. - Gamma heating ratio as function of mass. All specimens 1 by 3/4 inch (2.54 by 1.905 cm) slabs.

the experiment does not show a significant difference in gamma heating in aluminum and carbon (in W/g). The values for lead, tin, and zirconium are significantly greater than those for aluminum and carbon.

STATISTICS

The result for run 22 was rejected using Dixon's Criterion at a 90 percent probability level (ref. 4). The results of the other repeated observations were pooled to estimate the standard deviation for all the runs. This procedure gave a standard deviation of 4.1 percent for the values of $\Delta T/P$. This is an estimate of precision rather than of accuracy; however, the data reduction eliminates accuracy as a factor because only the relative heating is being determined. The propagation of this error through the the estimates of K_1, K_2, K_3, and R was calculated using standard error propagation equations. The estimated deviations for K_1, K_2, and K_3 and the range of standard deviations for the individual R values were as follows:

$$\sigma_{K_1} = 7.6 \text{ percent}$$

$$\sigma_{K_2} = 4.1 \text{ percent}$$

$$\sigma_{K_3} = 14.4 \text{ percent}$$

$$\sigma_R = 8.5 \text{ to } 12.2 \text{ percent}$$

These σ_R values are shown as error bands in figure 6.

A similar experiment was previously run in a facility having spent fuel elements as the gamma source. In that experiment the precision was improved because of the constancy of the source level, but the spectrum of the source was probably softer than the MUR spectrum. The results of that experiment (ref. 5) showed the same general trends as the data reported here; for example, the response of the 4 gram lead specimen was greater than the response of the 17 gram aluminum specimen. Thus those results give qualitative support to the results presented here.

SUBSEQUENT EXPERIENCE

The calorimeter was used to measure the value of R for an experiment mockup (fig. 7). An estimated value was obtained by determining R for a lead platelet of the same surface-to-volume ratio as a solid lead cylinder of the same mass and length as

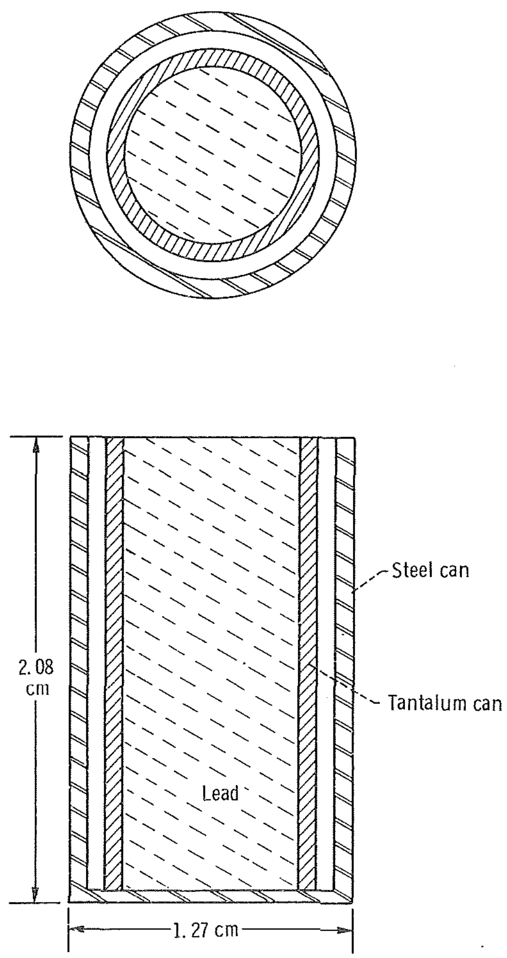

Figure 7. - Experiment mockup used in calorimeter.

the experiment mockup. This estimated value, from figure 6, was R(estimated) = 1.30. A measurement with the experiment mockup in the calorimeter gave a value of R(measured) = 1.46. The agreement is not bad considering the difference in geometries. The measurement proved the need for and usefulness of the calorimeter.

CONCLUDING REMARKS

Of course, the data are perfectly applicable only for the configuration that was measured. However, it is the authors' opinion that they can be used for any slab geometry configuration near a nuclear reactor in a light-element scattering medium.

The results of the experiment clearly show the magnitude of the effects of atomic number and thickness of a material on the gamma heating the material will experience in a nuclear reactor environment. While this work was principally concerned with effects on reactor experiments, the results can be applied to other reactor problems as well. It is the authors' opinion that additional analytical and experimental work is needed to obtain complete information for all geometries, materials, and gamma spectra.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 26, 1970,
120-27.

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